

Patent Application of

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for

Adaptive Slope Compensator for Current Mode Power Converter

Field of Invention

This invention relates to the power converters and more specifically to current mode power converters.

Background of the Invention

Various power converters are presently available for transforming an unregulated input voltage to a regulated output voltage with a specific magnitude. Various techniques of power conversion such as forward and flyback are well described as the prior art. Although the advantages of current mode control over voltage mode control has been amply demonstrated, the slope compensation must generally be added in the current loop to solve the instability problems. Many texts can explain the operation of current mode and the slope compensation, such as (a) Keith H. Billings "Switchmode Power Supply Handbook" McGraw-Hill Book Co., p3.148-p3.150 (b) Abraham I. Pressman "Switching Power Supply Design" McGraw-Hill Book Co., p105-p136 ; p143-p165. (c) Modelling, Analysis and Compensation of the Current-Mode Converter" Unitrode Corp. Application Note U-97 (d) "Practical Considerations in Current Mode Power Supplies" Unitrode Corp. Application Note U-111. However, there still exist several drawbacks in conventional slope compensation technologies. Thus, in order to solve the problem and improve the performance, mathematical analysis and practical circuit tests have been performed to establish the fundamentals of this invention. The characteristic analysis of conventional slope compensation are listed as follows,

(A) Advantage I: Slope compensation stabilizes the current loop

A general circuit of current mode power converter is shown in Fig. 1, its symbols defined are:

Pwr: power converter

N_P : primary turn ratio of T_M

L_P : primary inductance of T_M

I_P : primary current of T_M

I_{PA} : primary average current of T_M

I_{SP} : secondary peak current of T_M

T : switching period of Pwr

T_{OFF} : turn-off time of T

V_{IN} : input voltage of Pwr

V_{err} : output voltage of the error amplifier

V_{RP} : sensed voltage of resistor R_P

T_M : power transformer

N_S : secondary turn ratio of T_M

L_S : secondary inductance of T_M

I_{PP} : primary peak current of T_M

I_S : secondary current of T_M

I_{SA} : secondary average current of T_M

T_{ON} : turn-on time of T

V_O : output voltage of Pwr

V_{SL} : voltage of slope compensation signal

There are two distinctly different operating modes of power converters, discontinuous and continuous. ^{when} a higher power conversion efficiency is concerned, the continuous ^{mode} is much more widely used than the discontinuous mode. The purpose of following analysis is to ^{determine} the criterion of stabilizing the current loop in which a minimum magnitude of the slope compensation has to be added, if the power converter is operating in *continuous current mode* or if the duty cycle of power converter is greater than 50 percent. Slope m is the down slope; $m = di/dt = V_o / L_s$. Fig. 2 shows the continuous mode current waveform, I_p and I_s . $I_{SA} = I_{SP} - (di/dt) \cdot dt = I_{SP} - (m/2) \cdot dt$; $I_{SA} = I_{SP} - (m/2) \cdot T_{OFF}$; $I_{SP} = I_{SA} + (m/2) \cdot (T - T_{ON})$. The peak voltage V_{RP} across the primary current-sensing resistor R_P is $V_{RP} = I_{PP} \cdot R_P = I_{SP} \cdot (N_s / N_p) \cdot R_P = [I_{SA} + (m/2) \cdot (T - T_{ON})] \cdot N_s / N_p \cdot R_P$. Adding the slope compensation to V_{RP} , this feedback signal is stated as $V_C = V_{RP} + (V_{SL} / T) \cdot \Delta T = V_{RP} + (V_{SL} / T) \cdot (\Delta T_{ON} + \Delta T_{OFF})$;

$$V_C = \frac{N_s}{N_p} R_P I_{SA} + \frac{N_s}{N_p} R_P \frac{mT}{2} + \Delta T_{ON} \left(\frac{V_{SL}}{T} - \frac{N_s}{N_p} R_P \frac{m}{2} \right) + \Delta T_{OFF} \frac{V_{SL}}{T} \quad (1)$$

Since an amount of energy delivered in a time T represents power, at the end of one period, power drawn from V_{IN} is $P = L_P I_P^2 / (2T) = [L_P \cdot (I_{PP}^2 - I_{PA}^2)] / (2T)$. But $I_{PP} = I_{PA} + \Delta I_P = I_{PA} + (V_{IN} / L_P) \cdot \Delta T$, ^{then} and thus

$$P = \frac{1}{2TL_P} (V_{IN}^2 \cdot T_{ON}^2) + V_{IN} \cdot I_{PA} \frac{T_{ON}}{T} \quad (2)$$

The current I_{PA} is an ^{energy which cannot} completely delivery to the load during the off (T_{OFF}) ^{time} and still remaining in the transformer. Thus the magnitude of the current I_{PA} is related to the T_{OFF} and T_{ON} . It is easily verified from equation (2), that the feedback loop regulates the output of power converter by controlling T_{ON} . The output voltage V_o is sensed and compared to a reference voltage in the error amplifier (EA). The amplified error voltage V_{err} (voltage loop signal) is fed to a voltage comparator and ^{compared} with the V_C (current loop signal). As shown in Fig. 1, the on time starts at the clock pulse of oscillator (osc) and ends when the V_C ramp equals to level of the V_{err} , thereby the adjustment of T_{ON} is ^{proportional} to the magnitude of voltage V_C and V_{err} . Mathematically the relationship between V_C and T_{ON} is $\partial V_C / \partial T_{ON} \geq 0$. The deviation from equation (1) can be stated as

$$\frac{\partial V_C}{\partial T_{ON}} = \frac{V_{SL}}{T} - \frac{N_s}{N_p} R_P \frac{m}{2}$$

This can be seen quantitatively as

$$\frac{V_{SL}}{T} \geq \frac{N_s}{N_p} R_P \frac{m}{2} \quad (3)$$

If the change of T_{ON} is ^{not} proportional to the V_C , $\partial V_C / \partial T_{ON} < 0$, then the feedback loop will ^{non-linearly} oscillate. Thus the criterion of equation (3) must be satisfied to insure the loop ^{stability}.

(B) Advantage II : Slope compensation improves ^{the} the linearity of current loop

Before adding the slope compensation, the signal V_C is equal to V_{RP} :

$$\Delta I_P = \frac{V_{IN}}{L_P} \cdot \Delta T \quad (4)$$

$$V_{RP} = (I_{PA} + \frac{V_{IN}}{L_P} \Delta T_{ON}) \cdot R_P \quad (5)$$

~~Equations~~ and demonstrate that This is seen from equation (2), (4), (5), when the output power remains constant, the T_{ON} increases and ΔI_P decreases as V_{IN} goes down. The current waveform corresponding to the V_{IN} and T_{ON} is shown in Fig. 3. The current feedback loop signal compared with the voltage feedback loop signal will control the output power and regulate the output voltage. It is obvious the control loop will lose the linearity and noise immunity as V_{IN} goes down. This disadvantage can be improved by adding the slope compensation.

$$\begin{aligned} V_C &= V_{RP} + \frac{V_{SL}}{T} (\Delta T_{ON} + \Delta T_{OFF}) \\ &= I_{PA} \cdot R_P + \frac{V_{SL}}{T} \Delta T_{OFF} + \Delta T_{ON} \left(\frac{V_{IN}}{L_P} \cdot R_P + \frac{V_{SL}}{T} \right) \end{aligned} \quad (6)$$

The slope compensation element remains a minimum linearity of the control loop.

(C) Disadvantage I: A dummy load or the minimum load is required to avoid the unstable oscillation during no load or light load conditions

conventional The current mode power converter per se are known, it will operate in discontinuous mode while the output is in no load or light load conditions and it may operate in continuous mode while the output power is high or the input voltage is low. A minimum magnitude of slope compensation must be added as equation (3), as long as the power converter operates in the continuous mode. While the power converter is operating in discontinuous mode, its slope compensation included current feedback loop signal V_C is

$$V_C = \frac{V_{IN}}{L_P} \cdot R_P \cdot \Delta T_{ON} + \frac{V_{SL}}{T} (\Delta T_{ON} + \Delta T_{OFF}) \quad (7)$$

This signal waveform is shown in Fig. 4; illustrating the mechanism of a nonlinear deviation in the power control. If the signal V_{err} goes down due to the regulation, its voltage move from point C to point A or point B will cause a nonlinear deviation. Since the voltage level of point A is equal to point B, but the on time (T_{ON}) of point A and point B is different, The difference is ($T_{ONB} - T_{ONA}$) which causes a deviation P_d in the power control.

$$P_d = \frac{V_{IN}^2}{2TL_P} (T_{ONB}^2 - T_{ONA}^2) \quad (8)$$

Because of this, the effect is then an oscillation which commences at every change in signal V_{err} and which may continue for some time. Two conventional approaches for solving this problem are (a) To equip with a dummy load in the output. This yield $[I_P \cdot R_P > (V_{SL}/T)]$ during the no load or light conditions. However this will consume a power of the dummy load. (b) To require consuming a minimum power in the load. However this cannot meet the requirements of the power management. The embodiment of power management is to manage the system only consuming the power during the operation. And no power, or few power is consumed during the non-operation (sleep mode). With

respect to the power converter in a power management application, ^{conserving} how to save the power in the no load or light load conditions is a major requirement. ¹

(D) Disadvantage II : Less than ideal line voltage regulation

Consider how the power converter regulates against line voltage changes. As V_{IN} goes up, the V_o will eventually go up. Then after delay in getting through the voltage feedback loop, V_{err} will go down and the output voltage will be brought back down. Beside the mechanism of this, there is a shortcut correction in the current mode operation. As V_{IN} goes up, the slope of current I_p increases and hence the slope of the ramp of V_{RP} increases. Now the faster ramp equals V_{err} and the on time (T_{ON}) is shortened. Output voltage changes resulting from input voltage changes will be smaller in amplitude and shorter in duration because of this feedforward characteristic. The output voltage V_o is

$$V_o = V_{IN} \frac{N_s T_{ON}}{N_p T_{OFF}}$$

By using equation (7), if $V_c = V_{err}$, then we obtain

$$T_{ON} = \frac{V_{err}}{\left(\frac{V_{IN}}{L_p} \cdot R_p + \frac{V_{SL}}{T}\right)} \quad (9)$$

It can be seen we can find that the loop gain of this feedforward characteristic will be reduced by increasing the magnitude of slope compensation V_{SL}/T . Thus, ^{increasing} the magnitude of slope compensation will decrease the loop gain of current feedback loop and then reduce the capability of line voltage regulation. ^{the}

Figures (5) and (6) show two conventional methods of implementing slope compensation. ^{these methods, however,} There are unable to solve the problems in the previous description and unable to operate in wide input ranges (V_{IN}). ^{one}

Objects of the Invention

In view of the above advantages and disadvantages with the ^{conventional approaches} prior approach, the object of the present invention is to provide a ^{novel} solution to ^{avoid} these disadvantages and achieve a ^{wide input ranges} power conversion. Besides, the objects of the present invention are :

- to improve the power conversion efficiency and save the energy.
- to shrink the volume of power converter and save the material costs.

These objects are realized in a novel slope compensation construction which allows the power converter to operate in continuous mode under the medium load or heavy load condition. And, no minimum load, ^{furthermore} no dummy load is required under the light load or no load conditions. The adaptive function of the present invention ^{the} which will enhance the linearity of control loop in response to a lower input voltage and permits a higher duty cycle (T_{ON}/T_{OFF}), thereby ^{necessitating only} a smaller input capacitor ^{is only need}. In an off-line power

converters, this high voltage, high capacity electrolytic capacitor ^{is} expensive and large. It is much more compact and cost effective to use a smaller input capacitor.

Summary of the Invention

In accordance with the present invention, a programmable current source comprises a capacitor, generating a slope ^{signal}. This slope signal is added to current feedback loop for slope compensation, ^{the} slope signal is synchronized with the switching signal of power converter via ^{the} connection of a diode; the input of ^{the} programmable current source having a resistor, coupled to the voltage feedback loop of power converter, and generating a slope signal in response to the input voltage and output load of power converter wherein the slew rate and magnitude of the slope signal is responsive to the input voltage and output load, and the signal width of the slope signal is equal to the pulse width of switching signal of power converter.

The Drawing

Brief Description of the Drawings

Fig. (1) is a simplified circuit illustrating ^{a conventional} current mode power converter;

Fig. (2) shows ~~the~~ continuous mode current waveforms;

Fig. (3) shows the current waveform under relatively high and relatively low V_{IN} ;

Fig. (4) is the current loop feedback signal, in which the slope compensation signal is added, ^{thus illustrating} the mechanism of a nonlinear deviation in the power control;

Fig. (5) and (6) show, respectively, two forms of prior art circuits;

Fig. (7) is a schematic diagram illustrating a preferred embodiment of the invention; and

Fig. (8) is the voltage waveform of ripple in input capacitor.

Detailed Description of Preferred Embodiment

Fig. (1) shows ⁽⁷⁾ an embodiment of current mode power converter constructed in accordance with the invention. PWM controller U_1 is a general control circuit for current mode power conversion. The switching signal V_{sw} (the output of U_1) drives a switching MOSFET Q_2 . A transformer T_M is placed in series with V_{IN} and Q_2 for the power transfer. Switching frequency is determined by capacitor C_3 and the oscillator (osc) in U_1 . Due to the Latch of U_1 is set by osc and reset by the comparator (Comp) in U_1 , the on time starts at the clock pulse of osc and ends when the voltage level of signal from current feedback loop 200 equals to the voltage level of signal from voltage feedback loop 150. The voltage feedback loop consists of error amplifier U_3 and optocoupler U_2 . The output voltage of power converter, V_o , is sensed and compared to a reference voltage in the error amplifier U_3 . The optocoupler U_2 is required for the isolation in an off-line power converter, otherwise the amplified error voltage can be directly fed to the comparator of U_1 . Another input to the comparator is the current feedback signal in which the primary current of transformer T_M is sensed by resistor R_p , and it is coupled to U_1 via the low pass filter R_5 and C_5 . Adaptive slope compensator 100 has a pnp transistor Q_1 , and incorporates resistors R_1 , R_2 , R_3 to form a programmable current source. Power is supplied from V_R of U_1 , it is a constant voltage (reference voltage) output of U_1 . The output of the programmable current source, the collector of Q_1 , has a capacitor C_T connected

to ground, which serves to produce slope waveform, and provides the time constant for the slew rate of slope signal. A diode D_T is connected between the output of programmable current source and the output of $U_1(V_{sw})$, which serves to synchronize the slope signal 250 with the switching signal V_{sw} , 300. Bridge by the series of D_T and R_4 , slope signal 250 is added to the current loop 200. Via resistor R_1 , the input of programmable current source is connected to any suitable means, exemplified here to V_{FB} , a voltage feedback loop signal, and thereby the output current of programmable current source is effected by input voltage V_{IN} and output power P_O of power converter.

Operation

The operation of Fig (7) in accordance with the invention is as follows :

During the on time (T_{ON}), the switching signal V_{sw} is high and diode D_T is off, capacitor C_T is charged by the programmable current source. Mathematically this can be stated as

$$V_{SL} = \frac{I_{R3} \cdot \Delta T}{C_T}$$

If the gain (h_{FE}) of $Q1$ is enough high, then

$$I_{R3} = (V_{R2} - V_{EB(Q1)}) / R_3$$

$$V_{R2} = (V_R - V_{FB}) \cdot [R_2 / (R_1 + R_2)]$$

The equation can be written as

$$V_{SL} = \frac{\Delta T}{R_3 \cdot C_T} [(V_R - V_{FB}) \cdot \frac{R_2}{R_1 + R_2} - V_{EB(Q1)}] \quad (10)$$

$$\frac{\partial V_{SL}}{\partial V_{FB}} = \frac{-R_2}{R_3(R_1 + R_2)C_T} \cdot \Delta T \quad (11)$$

Since the change of V_{FB} is directly proportional to the change of V_{IN} and inversely proportional to the change of output power P_O , $\Delta V_{FB} = +K_1 \Delta V_{IN} - K_2 \Delta P_O$, where K_1 , K_2 are loop gain constants. The constant of voltage feedback loop. Thus, the equation (11) can be stated as :

$$\Delta V_{SL} = \frac{R_2}{R_3(R_1 + R_2)C_T} \Delta T \cdot (-K_1 \Delta V_{IN} + K_2 \Delta P_O) \quad (12)$$

During the off time (T_{OFF}), the switching signal V_{sw} is low, diode D_T is on, capacitor C_T is discharged and the slope signal is reset to zero. Since the slope signal is synchronized with the switching signal, the rising time ΔT of slope signal is equal to the on time T_{ON} . Thus equations (10) and (12) can be written as :

$$V_{SL} = \frac{T_{ON}}{R_3 C_T} [(V_R - V_{FB}) \cdot \frac{R_2}{R_1 + R_2} - V_{EB(Q1)}] \quad (13)$$

$$\Delta V_{SL} = \left(\frac{R_2}{R_1 + R_2} \right) \frac{T_{ON}}{R_3 C_T} \cdot (-K_1 \Delta V_{IN} + K_2 \Delta P_O) \quad (14)$$

In one specific implementation of the Fig. (7) arrangement, a 50W (P_O : 20V_{DC}/2.5A) off-line power converter, the input voltage is rated 90V_{AC} ~ 265V_{AC} RMS, using a small input capacitor C_{IN} as 68 uF (microfarad), 400 volt electrolytic device. An EFD-30 ferrite core was used, operating in continuous mode under the medium load and full load. The efficiency of 85% ~ 88% was obtained responding to the change of V_{IN} (90V_{AC} ~ 265V_{AC}). And, less than 2W was consumed under the no load condition. According to the principle of equations (13), (14) and the measurement in the implementation, following results are observed :